TITLE: Use of the SIMBAD Gun Dynamics Code for Modelling the In-Bore Dynamics of EM Launchers

USE OF THE SIMBAD GUN DYNAMICS CODE FOR MODELLING THE IN-BORE DYNAMICS OF EM LAUNCHERS

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Generic SIMBAD models of various Electro-Magnetic (EM) launchers have been used in the UK for studying model the in-bore phase and launch accuracy issues of such systems. Although many of features of the EM environment are not modelled with any degree of complexity, SIMBAD still provides a useful tool for investigating some of the dominant material and geometric influences on the in-bore dynamics and launch accuracy.
Modifications to the SIMBAD code allowed for the simulation of asymmetrical electro-magnetic forces acting on the projectile. Other modifications allowed for the simulation of some of the time varying asymmetries in the forces on the projectile. These have demonstrated that there may be additional EM influences contributing to in-bore projectile balloting.
Comparative performance data was produced for three shot designs (U4, U7 and U9 projectiles) simulated being fired from the 90mm IAP and Task C launchers, and highlighted their typical in-bore performance characteristics. Transverse accelerations on the projectiles showed typical peak values of 6,000g. Higher values and degradation in projectile performance was demonstrated due to increasing wear and distortion in the launcher's core when experimental bore straightness and wear were included.
Initial values for projectile exit conditions from the launchers were produced, which demonstrated increased sensitivity of shot jump, pitch and pitch rate in the vertical plane and some important differences between projectile designs.

INTRODUCTION

The Defence Evaluation and Research Agency (DERA) has conducted applied research for the UK Ministry of Defence over the past five years into the use of Electro-Magnetic (EM) launchers and projectiles. One strand of this work has investigated the firing dynamics of the system in relatively simple terms using the existing 'Gun dynamics' code of SIMBAD [1]. Previous to this, limited studies had been conducted using RAMA [2] to model the US 90mm SPARTA gun [3] and with SIMBAD to model a generic 90mm projectile [4].

EM gun systems differ in several important respects from conventional gun systems, namely: anisotropic composite barrel structures, hyper-velocity in-bore projectile dynamics and interaction of rapidly varying electromagnetic, thermodynamic and mechanical deformation fields. These features cannot be modelled directly with any degree of complexity within the

SIMBAD code. However, its use does provide a tool for investigating some of the predominant material and geometric influences on the system dynamics for low computational cost and rapid solution, thus allowing for investigations into a wide variety of input parameters.

Over a period of three years, work was performed on the following: adding code to account for some of the special effects of the EM launchers and projectiles; refining the input data used for the SIMBAD model, and performing basic sensitivity studies to establish data on a number of gun and projectile designs. In particular work has concentrated on the 90mm IAP and Task C launcher systems firing the U4, U7 and U9 shot variants.

MODELS

Using commercially available software (Solid Edge CAD [5], Algor FEA [6] and Ideas FEA [7]), numerous CAD and FEA models of the launcher and projectile components were built (see Figures 1 to 3 below). These are typical techniques used to generate launcher and projectile input data for the SIMBAD models.

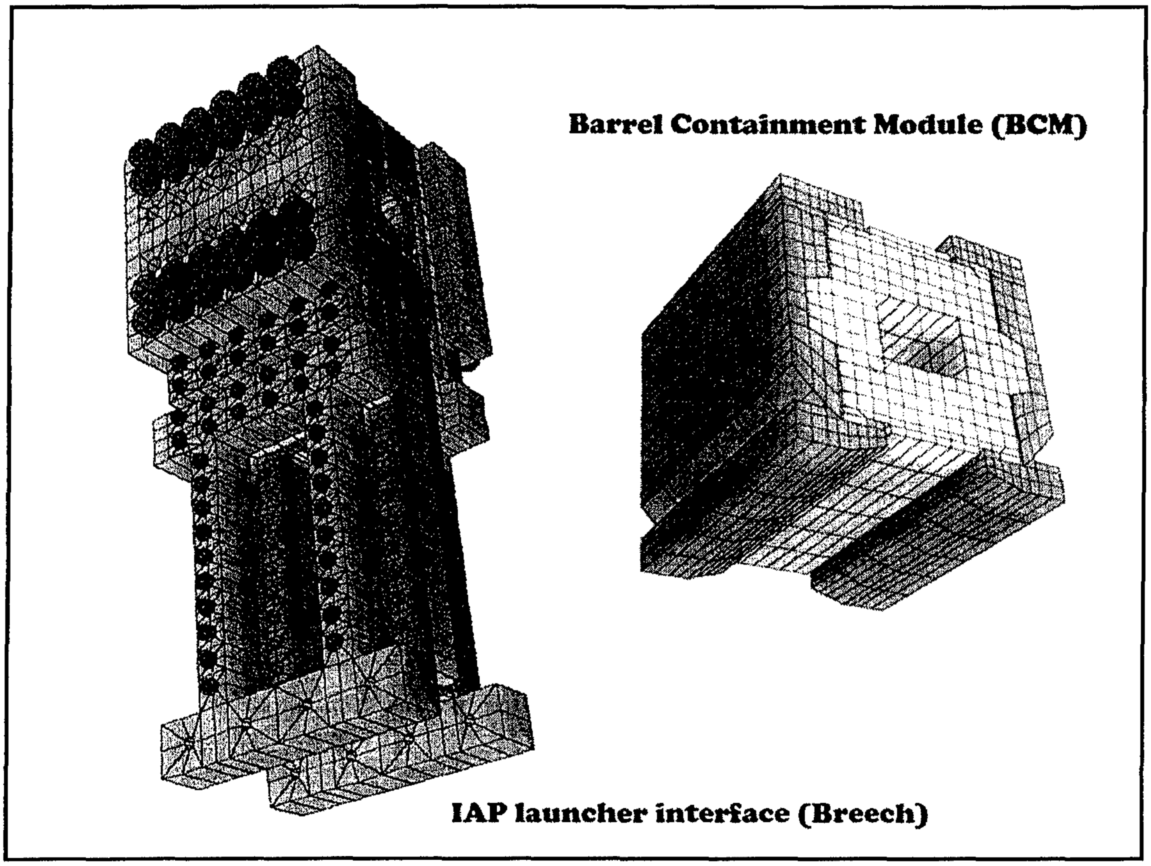

FIGURE 1. Algor FEA 'brick' models of the IAP launcher interface and BCM.

The CAD models are able to provide accurate mass properties for components e.g. mass, centre of mass, inertia. This can be used directly in SIMBAD for items such as the projectile's

armature which were represented as 'lumped masses', and indirectly to check mass data generated by SIMBAD, such as overall projectile mass. The FEA models are able to provide stiffness data for component-to-component interfaces e.g. projectile/barrel contact stiffnesses, elevating gear stiffness, and indirectly to check the frequency response of the model components, e.g. modal analysis of overall projectile assembly using various boundary condition constraints.

IAP BARREL

There are several ways in which the IAP launcher could have been modelled within SIMBAD. The approach adopted in this instance assumed that the majority of the bending stiffness within the barrel structure is derived from an 'I' section support beam running the length of the launcher and two 'U' section connecting beams running down the sides of the Barrel Containment Modules (see Figure 2). This also assumes that both the core and the BCMs do not contribute greatly to the bending stiffness.

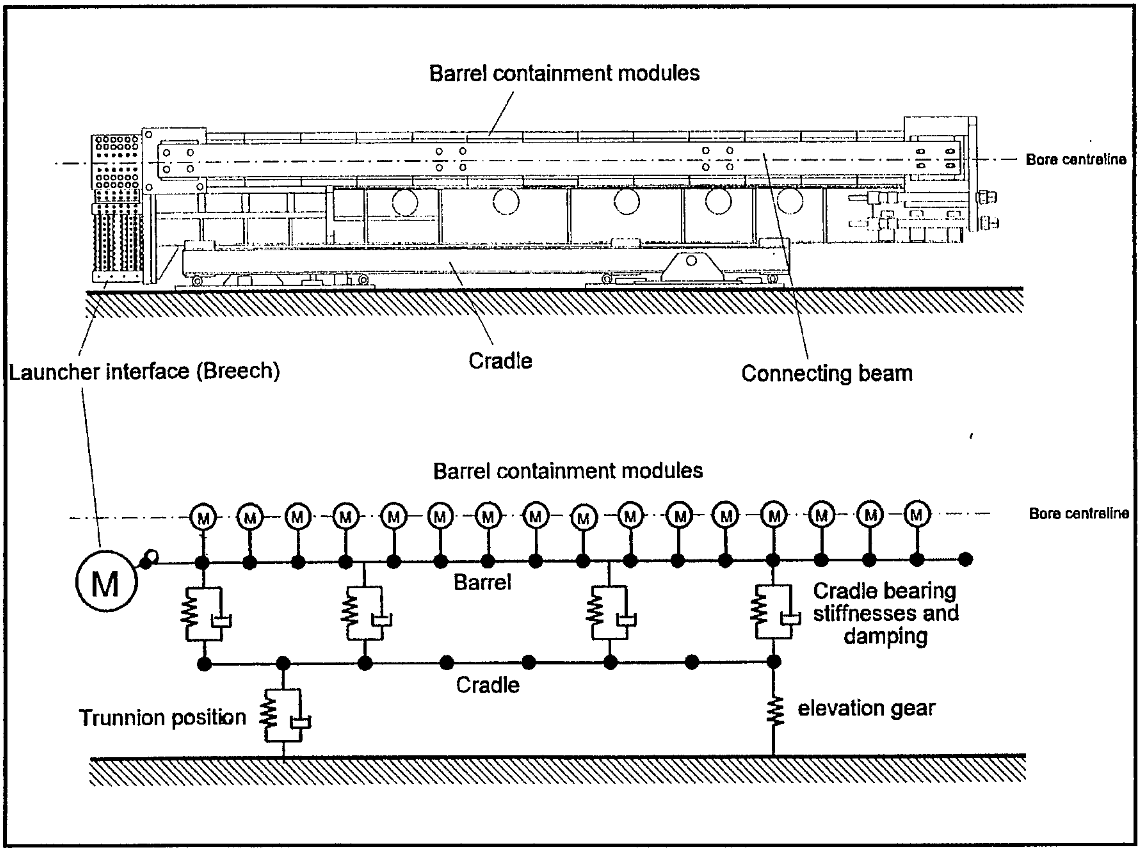

FIGURE 2. SIMBAD FEA 'beam' element model of the 90mm IAP EM launcher.

The first of these assumptions was backed up by a simple comparison of the bending stiffness of the support beams with that of the copper-G10 core, assuming the latter to be a contiguous unit of similar length. From simple theory the ratio of the stiffnesses was found to be 200:1. The mass and inertia of the core, approximated from modelling to be in the order of

552.0 kg [6], was not ignored but added to the 'lumped masses' of the BCMs described below.

BARREL CONTAINMENT MODULES (BCMs)

The fourteen BCMs of the IAP launcher are designed to hold the copper-G10 core in place. The assumption that the BCMs were not contributing to the structural bending stiffness of the barrel was based on experimental evidence from firings which indicated that these behave and move independently of one another, and possibly of the support and connecting beams, during in-bore shot travel. Due to this, and the compact nature of their structure, they were modelled most effectively in SIMBAD as lumped masses. These lumped masses are added at the relevant barrel nodes so their gross behaviour on the barrel structure was included.

The barrel nodes of the SIMBAD IAP barrel model were modified accordingly by redefining the offsets of centroid position of the cross-section from the bore centreline, i.e., the true position of any node is x, $y+y_{offset}$, $z+z_{offset}$. In this instance the y offset was a constant -0.3225m to account for the mismatch between the apparent and real bore centrelines.

To try and optimise the effects the BCMs have on the structure, the number of barrel beam elements was initially limited to 17, thus allowing for nodes 3 through to 16 to accept the mass of one BCM each. The code was later modified to allow for 63 elements to represent the barrel thus allowing experimental barrel bore straightness to be better represented.

TASK C BARREL

The first model constructed for the Task C EM Gun analysis was a 3D linear brick element model of the Task C composite barrel. The Task C barrel is complex in its construction and the information gathered detailing its internal structure was limited. The second FEA model used linear beam elements to construct the model of the composite barrel. Two models were constructed. The first used multiple beam element sections to represent the separate materials associated with the composite barrel, i.e. copper rails, insulator, laminate containment structure and outer skin. The second variant combined the properties of the first model to produce single beam elements representing the cross section of the Task C barrel. Data from this model was then used to produce the SIMBAD gun dynamics model.

To analyse the behaviour of the composite barrel, free-free normal modes analyses were performed to calculate the natural frequencies and mode shapes for each of the barrel models constructed. Results (see Table 1) showed that there was good correlation between the natural frequencies for the first two bending modes of the brick and beam barrel models. The multiple beam element model produced closer values of natural frequency than the single section beam model to the brick element model.

As a further check linear static analyses were performed to predict the bending moment stiffness of the barrel models. Each analysis supported the barrel as a simple cantilever beam, then applying a load to the other end of the structure. The results (see Table 1) showed a better correlation between the bending moment stiffnesses of the two beam models giving good confidence in the models. Again the stiffnesses are slightly higher than the brick model but this can be expected due to modelling assumptions and simplifications that were made.

TABLE 1. Predicted natural frequencies for the Task C barrel models.			
Mode type↓ / Model Type →	IDEAS 'Brick' element model	IDEAS 'Beam' element model	SIMBAD beam element model
Natural Frequency (First Bending, Hz)	16.82	17.44	18.04
Natural Frequency (Second Bending, Hz)	49.47	51.84	57.07
Natural Frequency (Third Bending, Hz)	94.30	104.6	115.51
Natural Frequency (Fourth Bending, Hz)	161.01	174.47	193.00
Bending moment stiffness (Nm/rad)	5.544E+10	6.413E+10	6.343E+10

The Task C cradle was constructed as a detailed FEA model using linear 'shell' elements. The SIMBAD cradle model was created using 'beam' elements. Certain assumptions and approximations were made during construction of this model in order to produce an accurate comparison with the detailed shell element model. Cross-sectional properties were obtained from the 'shell' element model at selected intervals along its length and converted into beam elements. Lumped masses were used to represent the saddles at the relevant nodal positions on the 'beam' element model. A mass property comparison between the 'shell' and 'beam' element cradle models showed good correlation in mass, inertias and C of M.

A normal modes analysis was performed for the elevating mass models (barrel and cradle) with cradle-to-ground boundary conditions in place. The natural frequencies of the structure were obtained and are shown in Table 2 below.

TABLE 2. Predicted natural frequencies for the Task C elevating mass models.		
Mode type↓ / Model Type →	IDEAS 'Brick' element model	SIMBAD 'beam' element model
Vertical First Bending (Hz)	32.0	39.3
Horizontal First Bending (Hz)	51.9	56.4
Vertical Second Bending (Hz)	75.8	72.2
Vertical Third Bending (Hz)	83.2	86.3

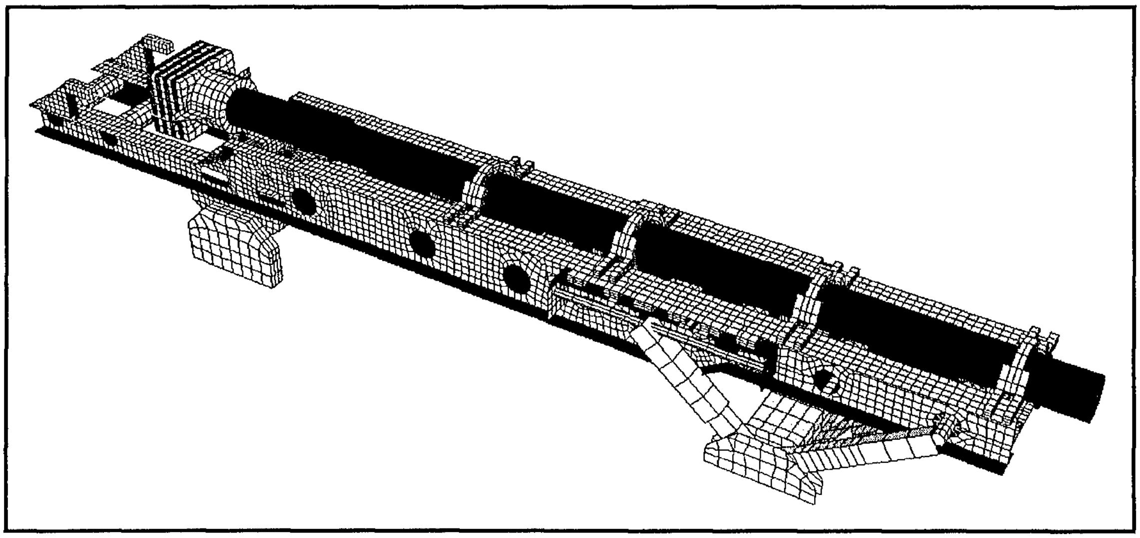

FIGURE 3. IDEAS FEA 'brick' and 'shell' element model of the Task C EM launcher.

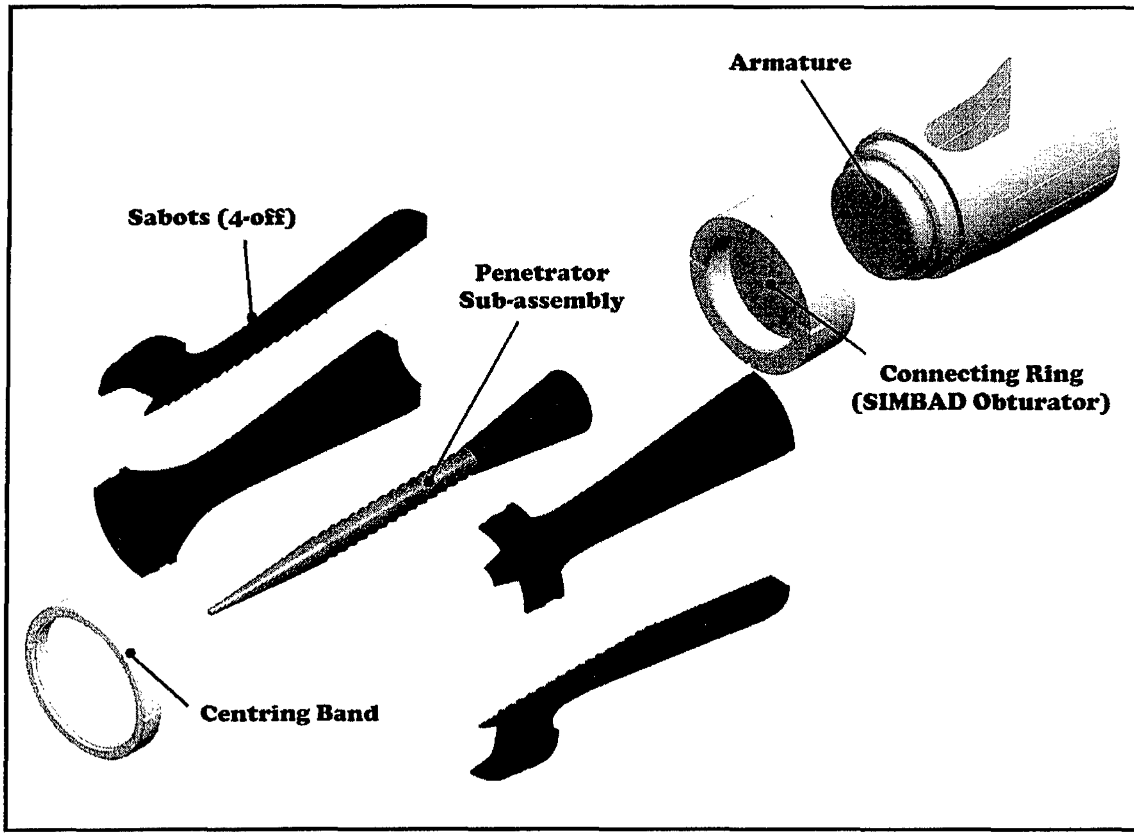

FIGURE 4. Components of the EM APFSDS projectiles.

Preliminary use of the IDEAS and Algor FE analysis software was undertaken when constructing the EM projectiles. Using 'brick' element models of the full projectile assemblies, the U4, U7 and U9 projectiles were analysed with and without the armature connected and compared to the equivalent SIMBAD 'beam' element models (see Figure 5 below). Table 3 below shows some typical results obtained from a free-free modal analysis comparison without the armature connected. As might be expected, the U7 variant has the higher natural frequencies since it is the shortest in length. Also, the carbon composite sabot of the U7 and U9 is slightly stiffer than that of the aluminium sabot of the U4.

All projectiles were modelled as two-piece (sabot and penetrator) shots within SIMBAD (See Figure 6 below). Typical assumptions for this type meant that all four sabot petals are composed of a single piece of material; all screw threads between components, e.g. between the sabot and penetrator core, are based on the mean thread depth for the components interface; all components exhibit isotropic material properties.

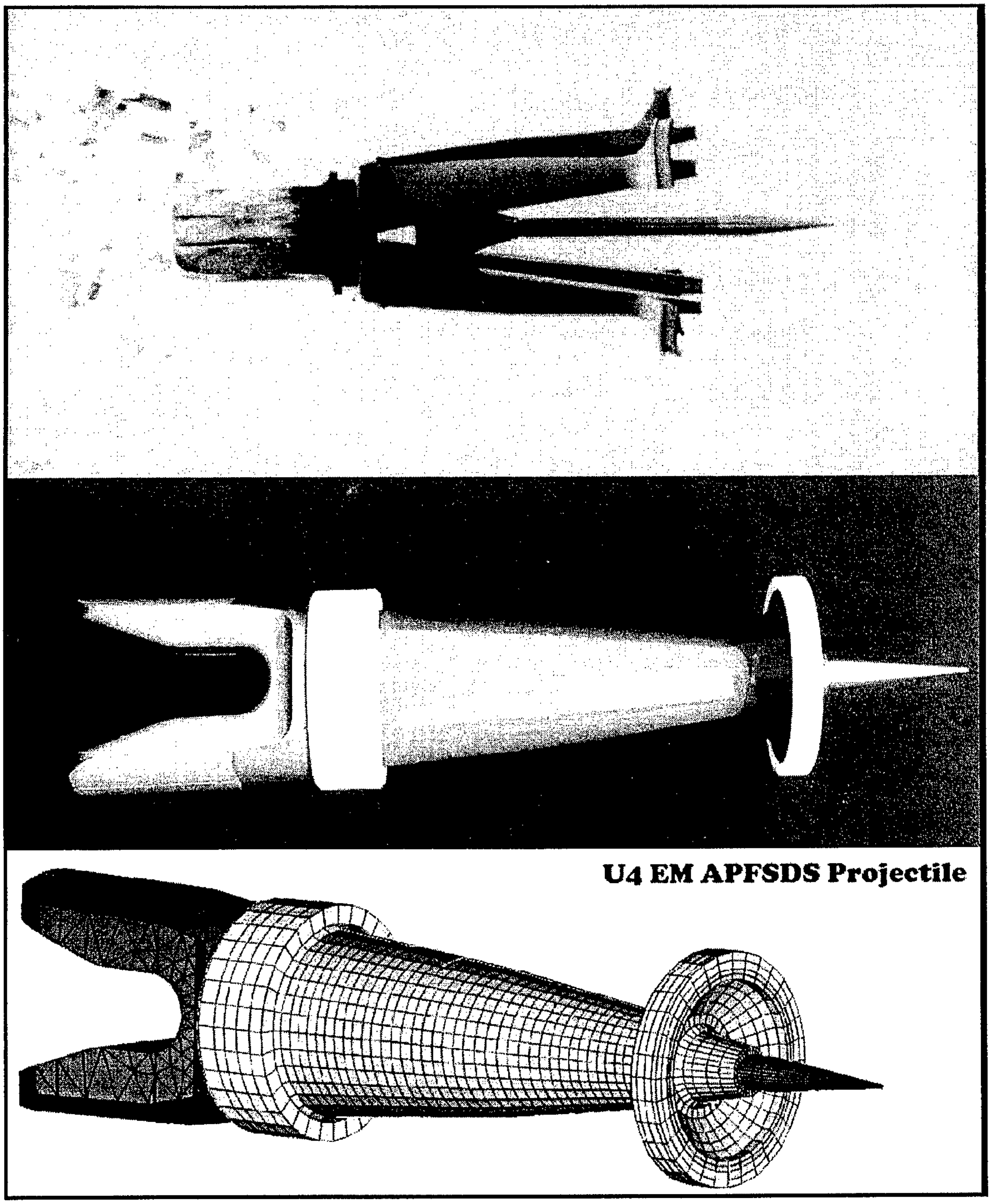

FIGURE 5. Typical IDEAS FEA 'brick' element model of the U4 EM projectile.

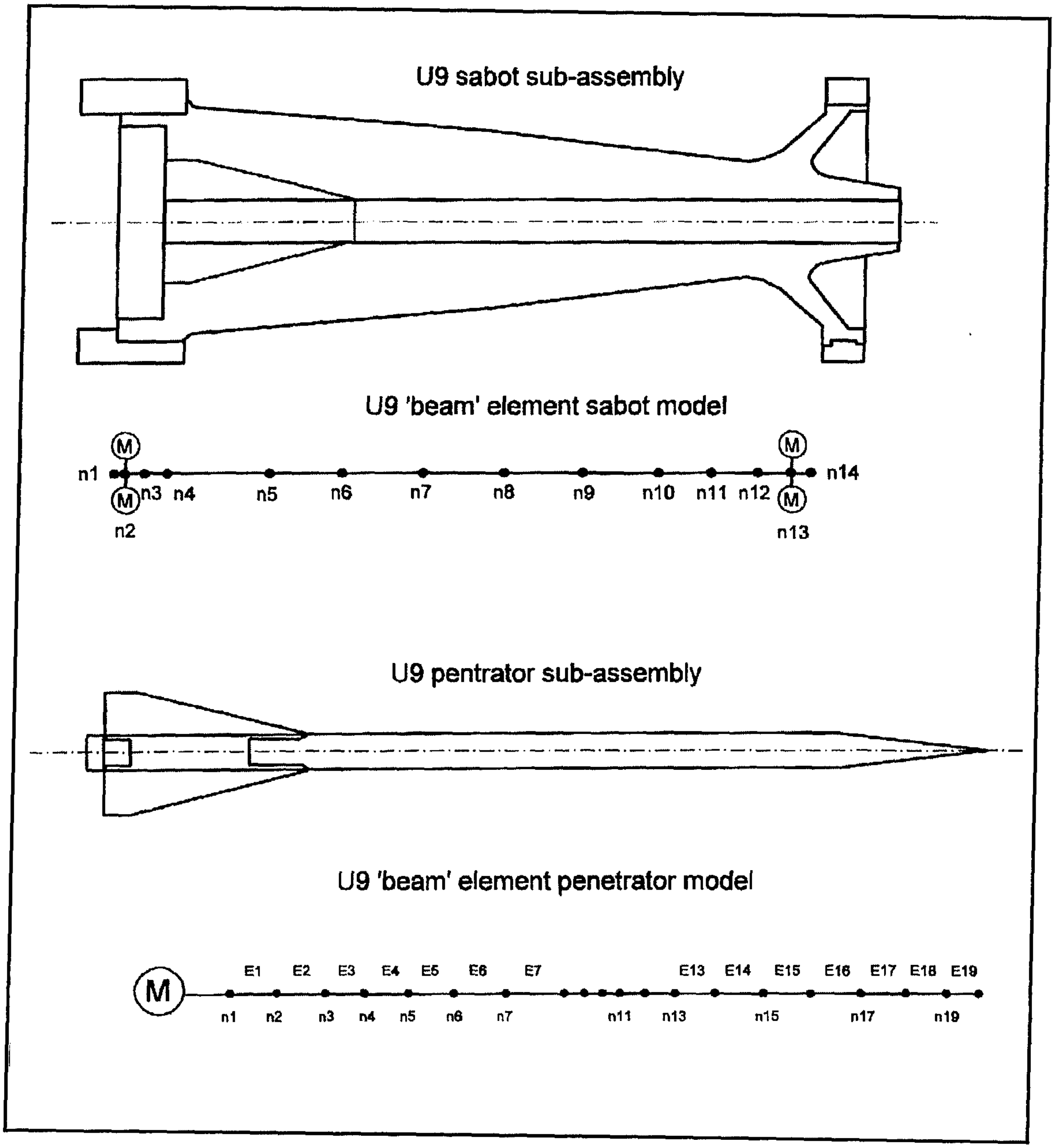

FIGURE 6. Example of SIMBAD 'beam' element model for the U9 APFSDS projectile.

TABLE 3. Free-free natural frequencies of the U4, U7 and U9 projectiles, less armature.						
Mode Type	U4		U7		U9	
	Brick (Hz)	Beam (Hz)	Brick (Hz)	Beam (Hz)	Brick (Hz)	Beam (Hz)
Bending 1	1966	1964	2020	2207	1558	1528
Bending 2	2304	2134	2966	3153	2607	2491
Bending 3	4097	3586	4905	5389	4099	4235
Bending 4	7329	7874	-	-	-	-

PROJECTILE STIFFNESS CALCULATIONS

The contact stiffnesses used in SIMBAD between the projectile and the barrel are one of the most critical areas when considering the in-bore dynamics of the shot. For the purposes of the SIMBAD gun dynamics simulation, a significant simplification is made in their representation, and is achieved using a series of spring/damper elements acting between nodes on the shot and barrel models. Stiffness values were calculated for the following parts of the projectile: connecting ring (SIMBAD obturator or driving band) radial and moment stiffnesses, front centring band radial stiffness and armature radial stiffnesses.

2D and 3D FEA models of the projectile components were constructed in IDEAS to calculate static deflection and hence stiffness. The values found varied between projectile and are summarised in Table 4 below.

TABLE 4. Projectile stiffness values used for the U4, U7 and U9 APFSDS projectiles.				
APFSDS Projectile	Radial centring band (N/m)	Radial connecting ring (N/m)	Radial armature (N/m)	Moment connecting ring (Nm/rad)
U4	8.800E+07	5.450E+08	1.000E+07	2.560E+05
U7	1.250E+08	2.420E+08	0.939E+07	3.750E+06
U9	7.500E+07	3.100E+08	0.960E+07	1.240E+05

The increased thickness of the U7 connecting ring compared to that of the U4 and U9 gives rise to a lower radial stiffness but a much higher moment stiffness, which can be confirmed by simple analytical calculations. The armature radial stiffnesses vary little between the projectile variants as expected because physical dimensions vary little between them.

ADDITIONAL ELECTROMAGNETIC LOADING EEFECTS

One difference that is apparent between a conventional gun and an EM gun is the method by which the recoil force is passed into the launcher. In a conventional gun the force of the gas pressure on the breech face pushes the recoiling mass rearwards. This is simplified in SIMBAD by the application of this pressure force on the breech node (normally node 1).

At the time this work was performed the method of recoil force application on an EM rail launcher was still not fully understood, but one theory suggested it was transferred to the barrel at the point at which the projectile's armature was within the core. The recoil force was

thus seen to travel with the shot up the barrel. Subsequent work has shown this to be incorrect, with this type of model more representative of a coil gun than a rail gun. The main recoil effect in an EM rail gun is still believed to act primarily at the breech. However, for this study both the 'conventional' and 'travelling' recoil force models were used in the SIMBAD analysis.

Two further modelling approaches were also used to demonstrate possible additional second order effects that the time varying Electro-Magnetic field is having on the projectile during its in-bore travel. These have not been derived from first principles, and as such they were merely used to demonstrate possible mechanisms by which additional pitch and yaw may be induced in an EM shot. Modelling of variable armature contact was concerned with the possible variation in the armature-rail contact surface during in-bore travel. In a conventional gun, the horizontal component of the applied shot base force (F_H) is given by Eq (1):

$$F_H = F_B \cdot \alpha_y \tag{1}$$

where F_B is the shot base force in the x direction and α_y is the rear band yaw angle with respect to the barrel and assumed to be small. In the armature of an EM gun the contact between rail and armature will vary depending on the yaw angle. It can be reasoned that as the yaw angle increases the surface area of contact on one side of the armature increases, whilst on the other it decreases. This leads to a different current flow in the two halves of the armature and a change in the current density, leading to an increase in the horizontally applied force on the shot. In simple terms this was modelled by adding an additional force to Eq (1), defined here as the "EM shot force yaw constant" (K_y):

$$F_H = F_B . \alpha_y .(1 + K_y) \tag{2}$$

To induce initial yaw in the projectile a small C of M offset was introduced into every SIMBAD run.

The other attempt at modelling additional secondary EM effects concerns the point of application of the shot base force. If the projectile and armature's horizontal axis is coincident with the barrel's then the current flow will flow evenly through the armature. As the shot and barrel axes move apart, the current path will move also. In a conventional gun, if the shot moves upwards by δ_y, the point of application of the shot base force will remain approximately in the centre of the round, i.e., on the shot's horizontal axes. Due to the changes in the current flow, it could be argued that this is no longer the case in an EM projectile, and that the point of application will move further, creating an additional pitching moment on the projectile. To observe the sensitivity of this effect the relative shot displacement is multiplied by a "EM offset base force constant" (K_o).

RESULTS

This paper is a summary of the work conducted over a three-year period. Within this time numerous studies were conducted with the models that have been described in the above

paragraphs. Due to the volume of data generated by the SIMBAD model, the following section highlights only some of the more interesting results of the SIMBAD dynamics studies.

IAP LAUNCHER MOTION

The amount of vertical movement in the barrel is very small, as the structure is extremely stiff. A maximum of ~0.8 mm is seen in the 'travelling recoil' model at the muzzle towards shot exit. For the 'breech recoil' model, the flexure of the barrel centreline appears to be relatively benign. In the 'travelling recoil' model, the profile shows greater displacements with higher dynamic curvatures induced in the barrel. It should be noted that this is due in part, to the limited number of elements used to represent the barrel. Barrel displacements are approximately 1000 times lower in the horizontal plane due to there being no off-axis masses.

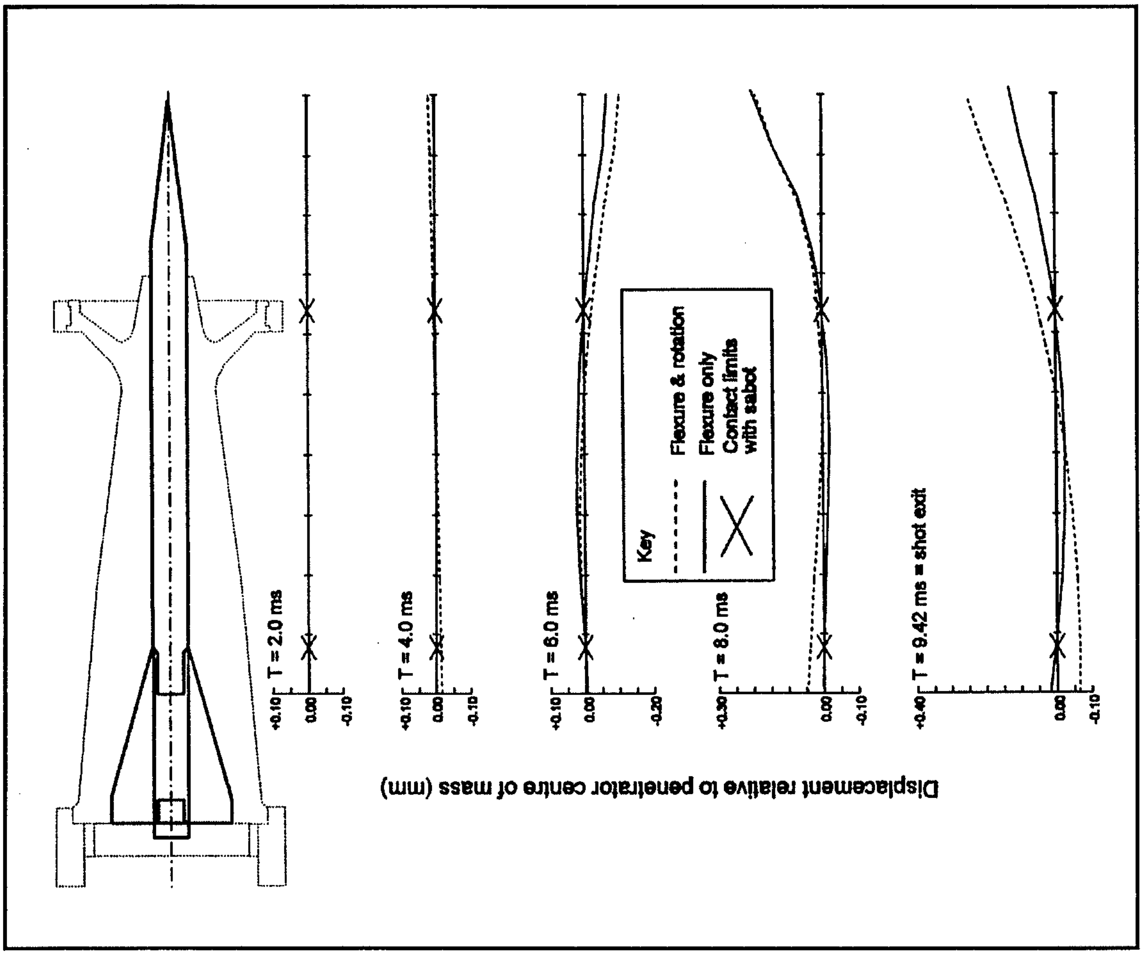

FIGURE 7. SIMBAD predicted U4 penetrator bending from an IAP launcher firing.

PROJECTILE MOTION

Figure 7 presents dynamic shapes in the vertical plane of a U4 penetrator fired from the IAP launcher with the 'travelling recoil' model. Each plot shows two penetrator shapes: pure flexure of the rod (solid line) and flexure and rotation of the rod (dotted line). The primary mode of vibration in the rod is that of the fundamental (first mode) frequency, distinguished by the 'cantilever' bending of the forward section of the penetrator forward of the sabot-penetrator contact point. Maximum flexure of the penetrator tip away from the neutral axis is in the order of 0.2 mm (travelling recoil) and 0.05 mm (breech recoil).

LATERAL SHOT LOADINGS

Transverse or lateral accelerations on an EM projectile during in-bore motion were predicted from the SIMBAD models for numerous conditions. Differences were particularly marked between the two recoil types. For the conventional 'breech recoil' peak accelerations were less than 2,000g. Only at the breech did the shot receive a 'kick' and a maximum acceleration of 3,500g was seen. For the 'travelling recoil' model the magnitude of the accelerations saw a peak of nearly 20,000g. Further analysis showed this to consist of two dominant frequencies: a relatively low frequency (0.3 kHz) probably associated with barrel motion, which produces a 10,000g peak, and a higher frequency (10.0 kHz) which increases the overall acceleration to 20,000g. These values are much higher than the design strength of the projectile. If the projectile were experiencing such accelerations it would almost certainly be breaking in-bore.

As a simple demonstration that these acceleration levels would break the projectile the bending and shear stresses within the penetrator for the in-bore phase were calculated. The point at the front of the penetrator-sabot interface (node 7) was chosen as one of the most likely areas of failure in shear (or bending). Maximum shear stress on the neutral axis was calculated. Shear stress at this point is plotted in Figure 8 for the two recoil models. For the 'breech recoil' model maximum shear stress values of 0.10GPa are recorded. For the 'travelling recoil' model maximum values of 2.0GPa are seen. The shear strength value of tungsten (assumed to be 0.87GPa), marked on the plot is crossed several times, indicating probable failure of the rod in shear.

SHOT EXIT PREDICTIONS

Table 5 shows some examples of shot exit conditions of a U4 projectile fired from the IAP launcher. Whilst predicted gun and shot jump figures are different between the 'conventional' and 'travelling recoil' models the standard deviations (SDs) for these exit parameters are not. Shot pitch and shot pitch velocities however show SDs that are far higher in the 'travelling recoil' model. This indicates lower launch accuracy and consistency in this model. More importantly the results show that these shot exit conditions are very sensitive to the recoil model type and that more effort is required to understand the issues of recoil force modelling in the EM gun if the models are to be more accurate.

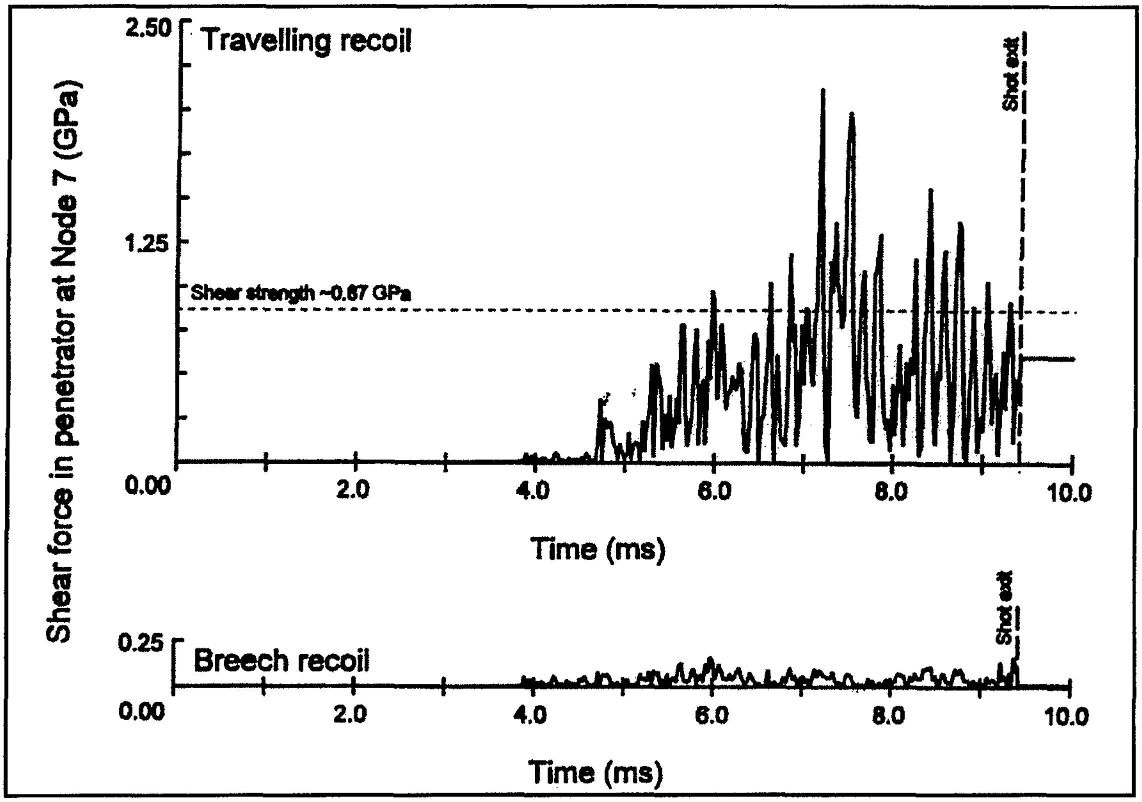

FIGURE 8. SIMBAD predicted U4 penetrator shear stress from an IAP launcher firing.

TABLE 5. Typical shot exit conditions for the two recoil models, U4 from IAP launcher.

Model		Vert. Gun Jump mils	Horiz. Gun Jump mils	Vert. Shot Jump mils	Horiz. Shot Jump mils	Shot Pitch angle mrad	Shot Yaw angle mrad	Shot Pitch Vel. rad/s	Shot Yaw Vel. rad/s
Breech recoil	Mean	-0.466	-0.055	-0.319	0.008	0.388	0.001	1.959	0.000
	SD	0.102	0.026	0.192	0.010	0.079	0.000	0.400	0.000
Travelling recoil	Mean	-1.064	-0.020	-0.758	0.011	0.685	0.001	1.671	0.001
	SD	0.041	0.018	0.115	0.010	0.621	0.000	1.694	0.001

PROJECTILE COMPARISONS

Overall, the in-bore dynamic behaviour of all three projectiles fired from the IAP launcher appeared to be similar. Subtle variations were seen in frequency responses of the various sub-assemblies, particularly the penetrator, which is to be expected due to the geometrical differences of the three projectiles.

The U4 projectile saw marginally higher forces, velocities and displacements in general. However, analysis of the vertical lateral acceleration of the sabot indicates that the U7 sees peak accelerations twice that of either the U4 or U9. The U7 and U9 also see higher

penetrator displacements relative to the sabot than the U4, again indicating higher loads at the sabot-penetrator interface.

The longer wheel-base of the U9 does not appear to impart more in-bore stability to the overall design as might have been expected. This is probably due to the greater influence of the launcher motion on the shot than a conventional gun system.

ARMATURE STUDIES

Studies were performed specifically to investigate the armature effects on projectile in-bore motion.

It is known from experimental firings that the armature is severely eroded during the in-bore phase and that its reduction in mass can be significant. A simple test in SIMBAD of reducing the armature mass by 40% appeared not to significantly alter the overall in-bore behaviour other than at shot exit. Here, sabot pitch angles were significantly different when armature mass was varied. Barrel motion heavily influences the behaviour of the projectile prior to shot exit, which in turn is a function of the SIMBAD barrel model and the launcher's geometry. It is probable that this apparent variation is due to one or both of these factors.

Variations in the position of the armature C of M and armature inertias showed negligible changes to projectile in-bore behaviour. This would be expected, as for example a change of 25% to the armature's inertia, results in a change of 10% to the projectile's pitch inertia. This leads to a change of approximately 4% to the pitch/yaw frequency, which is believed to be too small to be noticeable.

Changes in the contact stiffness between the armature and the bore were initially believed to be one of the more significant factors affecting EM projectile behaviour, since similar studies in conventional gun system indicated so [7,8]. For the IAP launcher in the vertical plane this did not appear to be the case. Despite using a large variation in armature stiffness only a marginal change in sabot/projectile response was observed. A much greater variation was seen in the horizontal plane. Decreasing the stiffness altered the yaw of the projectile, but the general behaviour was similar to the baseline. Increasing the armature stiffness had a much more marked effect, and the yaw angle was much lower for the majority of the in-bore travel.

The non-symmetry in the geometry of the armature and thus its contact stiffness appears to have an effect on projectile in-bore dynamics. In particular it appears that the more sensitive axis is that which runs through the legs. This is an important point to note, as the orientation of the projectile can be specific to each launcher. The contact stiffness of the armature may be time-position dependent and 'non-linear' due to any plasma layer that forms between armature and copper rails and should be considered when modelling its stiffness in SIMBAD.

CONCLUSIONS

Modelling of the in-bore dynamics of a number of EM projectiles fired from two EM launchers using the SIMBAD gun dynamics code. The code was modified extensively from its use on conventional gun systems simulation to account for some of the effects unique to the EM environment. Modelling has shown that amongst other factors projectile exit conditions are most sensitive to the choice of recoil force model used ('conventional' or 'travelling' recoil), the

magnitude of the time varying 3D asymmetric EM projectile loadings, and bore centreline profile and wear.

In the IAP launcher, the behaviour of the barrel model is the predominant influence in the behaviour of the projectiles in-bore due to a heavy muzzle mass dominating the response of the barrel. All projectiles see higher forces, accelerations and displacements towards the end of in-bore travel. In-bore dynamic behaviour of all three projectiles studied were similar. Subtle variations were seen due mainly to their geometrical differences.

Non-symmetry in the geometry of the armature and thus its contact stiffness appear to have an effect on projectile in-bore dynamics. In particular it appears that the more sensitive axis is that which runs through the legs. This is an important point to note since the orientation of the projectile in the bore can vary with each EM launcher system.

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